Rainfall Deposit on a Wall of a Building in a Storm

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Abstract

Rainfall on a vertical wall of a building in a storm is studied. Raindrops in wind are carried horizontally at the speed of the wind; and they fall with a terminal speed determined by their sizes. The deposition efficiency of rain water on a building was estimated from analogy with the deposition of fog particles on an obstacle in wind, and was tested by field experiments. The field experiments show that the efficiency of deposition is about unity in the case of heavy rain and high wind.

1. Introduction

Rainfall driven by wind hitting on the wall of a building usually runs off rapidly. However, sometimes in a heavy rain storm, like a typhoon, the amount of rain water on the wall becomes too large to drain off and it soaks through into the inside of the building, through windows and walls, forced by wind pressure, causing great damage.

The results of studies on the amount of rainfall deposited on a wall under storm conditions are presented in this paper.

2. Motion of Rain Drops in Wind

Rain drops in the free atmosphere fall vertically at a terminal speed determined by their sizes, and are carried horizontally at the speed of the wind. The response time of the raindrops to changing wind speeds is as small as 1 sec even for the largest raindrop[1]. Therefore the mean movement of raindrops in wind can be regarded as following the mean wind speed.

Thus the ratio of the flux of rain water through the horizontal plane, F_h, to that through the vertical plane, F_v, is equal to the ratio of the fall velocity of the raindrops, w, and the wind velocity, u, as shown as follows,

$$F_h/F_v = w/u. \tag{1}$$

The flux of rain water through the horizontal plane, F_h, near the ground is rainfall itself as defined in meteorology (hereafter described as horizontal rainfall, R_h, to avoid confusion). Therefore the flux of rain water through the vertical plane is described as follows,

$$F_v = R_h \cdot u/w. \tag{2}$$

If rain droplets are extremely small, they move with the air around an obstacle in wind, but they move in trajectories that allow them to strike the obstacle when the droplets are larger, owing to their larger momentum compared to that of the air.

The rate of deposition on a vertical unit area of an obstacle, which can be defined as rainfall on a vertical wall, or vertical rainfall, R_w, is related to the flux of rain water through the vertical plane as follows,

$$R_w = E \cdot F_v, \tag{3}$$

where E is the efficiency of deposition.

The deposition of water droplets suspended in the air on obstacles in winds has been studied in relation to icing on aeroplanes by many researchers.

According to Langmuir[2], the deposition of droplets of radius r, whose density is ρ_s, carried by a wind of velocity u, can occur on a spherical obstacle of radius s only when the following condition is satisfied:

$$\begin{aligned} K &= \frac{2}{9}\rho_s r^2 u / s\eta, \\ &\geq \frac{1}{12}, \end{aligned} \tag{4}$$

where K is a nondimensional parameter introduced by Langmuir and η is the viscosity of the air. Thus, below this value of K, the efficiency of deposition, E, is zero. Above this, it is a function of K and tends toward unity. It becomes 0.6 at $K=2$ and 0.9 at $K=10$. These relations were obtained on the assumption that the air flow around a spherical obstacle is of potential flow (ideal fluid) and the drag force on the rain droplets is according to Stokes Law.

From these results, a rain droplet comes to be deposited on a spherical obstacle of 10 m radius at a wind speed of about 7 m/sec for drizzle ($r=0.1$ mm) and about 0.07 m/sec for heavy rain ($r=1$ mm), assuming $\eta=1.8\times10^{-4}$ g sec^{-1} cm^{-1}. The efficiency of deposition becomes 0.9 at a wind speed of about 8 m/sec for heavy rain; but it is only 0.2 for drizzle even in a strong wind of 40 m/sec.

No theoretical or experimental studies have ever been made of rain water deposition on the walls of buildings, which are bluff and large compared to the parts of aeroplanes or rime collectors. This experimental study has been made on a small building.

3. Field Experiments

Field experiments were made at the Shionomisaki Wind Effect Laboratory of Kyoto University in Shionomisaki, Wakayama. The test building was a small observation house (Photo. 1). The rain water deposition on the wall, or the vertical rainfall, was measured on the southern face of the building, which is 7 m in width and 4 m in height, with a special vertical rain gauge. The vertical rain gauge has a 40 cm square rain collector fixed on the wall and rain water is guided through a tube into a recording rain gauge with high resolution. The horizontal rainfall was measured in the observation field near the building. The collector was a standard 20 cm rain gauge with wind shield, and the rainfall was recorded on the same chart as the vertical rainfall. Wind speed and direction were measured by a propeller type anemometer on the top of the wind tower on the observation house.

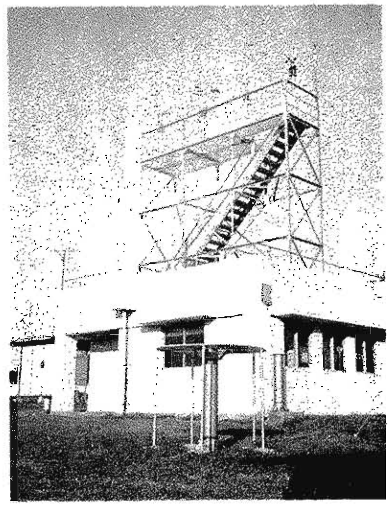

Photo. 1. The observation house

The observations were manually started when heavy rain was accompanied with strong wind. The observations are shown in Table 1. As each observation was continued as long as the same meteorological condition lasted, the length of each run is not the same. Four of these runs were observations made in typhoon winds.

Both kinds of rainfall, wind speed and wind direction were read and averaged every 6 minutes from the chart records. This time length was chosen owing to the mechanism of the recorder.

An example of time changes of observed values is shown in Fig. 1 which corresponds to Run 12 in Table 1, obtained during the passage of Typhoon 6909.

The wind was from SSW throughout the entire period; and the wind speed, which was the mean wind speed over the 6 min before the time plotted, was larger than 20 m/sec during most of the period. The horizontal and vertical rainfall (R_h and R_w) are shown in the second row. The rainfall shown in this figure is the rate of rainfall in the 6 min. before the time plotted. In the third row, the ratio of vertical and horizontal rainfall, R_w/R_h, is shown, and the value of the parameter $1/u \times R_w/R_h$ is at the bottom.

As is clear from this figure, the ratio of vertical and horizontal rainfall is larger than one and increases with wind speed. However the value of $1/u \times R_w/R_h$ is almost constant throughout the period and its mean value is 0.14 in this period.

The relation between the ratio of vertical and horizontal rainfall (R_w/R_h) and wind speed (u) in heavy rain when the wind direction is almost perpendicular to the wall (SSE, S and SSW) is shown in Fig. 2 using all the 6 min averaged values obtained in all the runs shown in Table 1. The lower limit of horizontal rainfall used in this analysis is 0.5 mm/6 min, e.i. 5 mm/hr.

As seen from this figure, this ratio can be regarded as proportional to wind speed. The exceptional points are seen when the wind speed exceeds 20 m/sec. As the collection efficiency of a horizontal raingauge decreases in a strong wind, these values have less significance. The regression line fitted by the least mean square method is shown in the figure. The proportional constant is 0.136, which is compatible with the value, 0.14 obtained in the example shown in Fig. 1 (Run 12).

Table 1. Mean state of each observation.

Run No.	Date	Time of start	Length of observation (hour)	Wind direction	Mean wind speed u (m/sec)	Mean rainfall intensity (horizontal) R_h (mm/hour)	Standard deviation of rainfall intensity σ_{R_h} (mm/6 min)	Mean rainfall intensity on the wall R_w (mm/hour)	Standard deviation of rainfall intensity on the wall σ_{R_w} (mm/6 min)	Mean ratio of rainfall intensity on the wall to the horizontal one R_w/R_h	Correlation coefficient of wind speed and rainfall*	Note
1	1968 9/26	06 : 54	6.0	ESE	5.2	7.1	0.2	3.1	0.2	0.44	−0.149	
2	1968 9/27	15 : 24	2.0	E	4.3	14.5	1.2	5.3	0.8	0.36	−0.231	
3	1968 12/ 5	08 : 35	2.0	S	6.9	15.9	1.1	9.9	1.1	0.61	−0.038	
4	1969 6/ 3	09 : 30	4.8	SE	4.1	11.4	0.9	3.8	0.3	0.33	−0.173	
5	1969 6/25	10 : 47	2.1	SSE	5.0	9.5	0.7	4.7	0.3	0.50	−0.624	
6	1969 6/25	13 : 11	2.0	SSW	9.6	3.0	0.1	3.1	0.1	1.05	−0.214	
7	1969 7/ 4	04 : 59	3.3	S	4.8	5.4	0.9	4.5	0.9	0.84	0.429	
8	1969 7/ 4	15 : 15	0.6	S	4.5	13.5	0.7	8.2	0.3	0.61	−0.218	
9	1969 8/ 4	11 : 24	8.0	SE	9.1	3.0	0.6	3.8	0.7	1.27	0.513	Typhoon 6907
10	1969 8/ 4	19 : 24	2.5	WSW	6.2	8.5	0.8	2.6	0.3	0.31	−0.014	Typhoon 6907
11	1969 8/22	21 : 25	1.5	S	10.2	17.3	2.2	20.0	2.6	1.15	−0.329	Typhoon 6909
12	1969 8/23	00 : 07	2.1	SW	18.6	19.2	1.6	43.5	2.5	2.26	−0.248	Typhoon 6909

* Averaging time being 6.0 minutes.

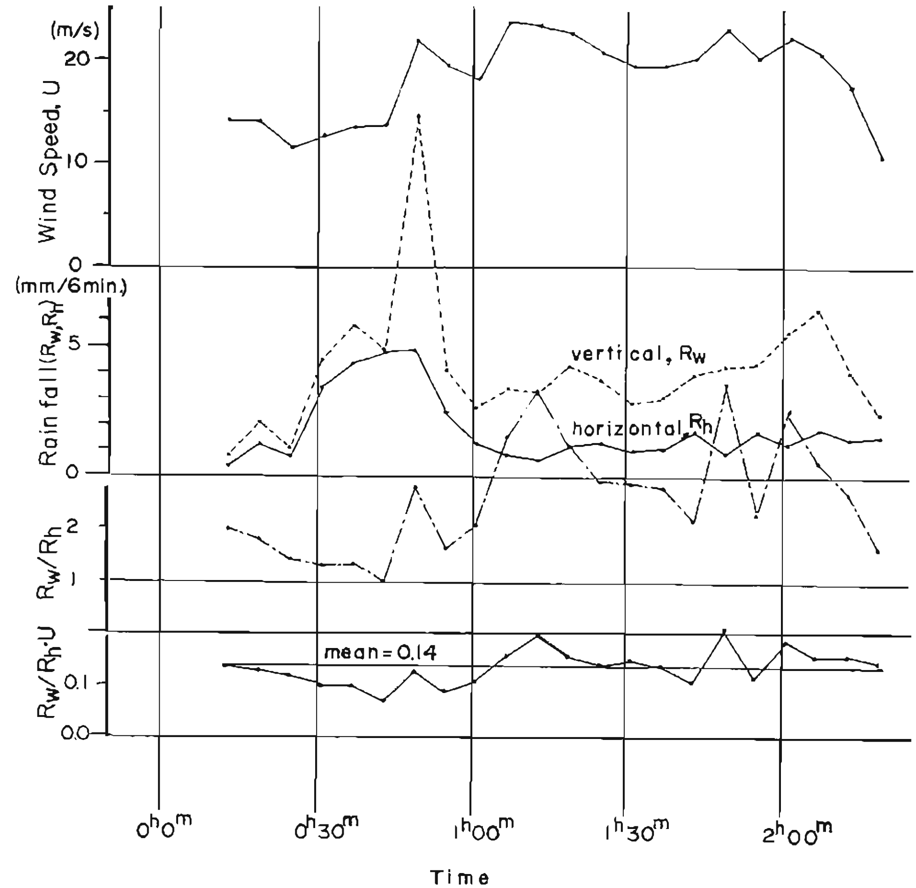

Fig. 1. An example of time changes of observed wind speed, vertical and horizontal rainfall and their related quantities.

The vertical rainfall, the deposition of rain water on the wall, R_w can be related to the horizontal rainfall, R_h, by using Eqs. (2) and (3) as follows,

$$R_w = E \cdot \frac{u}{w} \cdot R_h. \tag{5}$$

The observed fact that the ratio of vertical and horizontal rainfall is proportional to the wind speed in a rainstorm means that the value of E/w is nearly constant and is about 0.14. As the data are restricted to those obtained in heavy rain, the fall speed of the effective rain droplets is fairly large and may be in the range from 5 to 8 m/sec (radius being 0.5 to 1 mm). Therefore the efficiency of deposition, E, is estimated to be near unity.

As the measurement of drop size distribution could not be made, detailed discussion of the deposition efficiency of raindrops on a building is postponed to future studies.

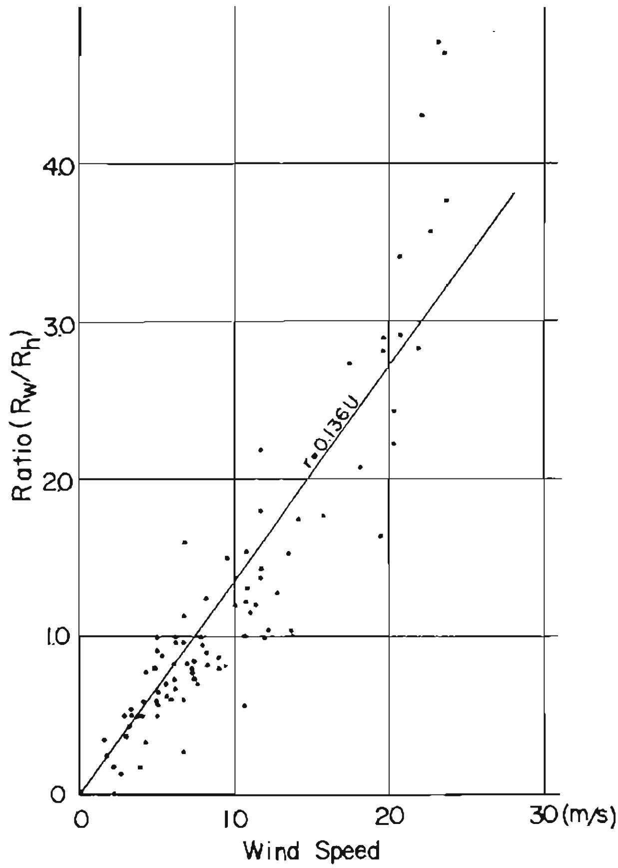

Fig. 2. Variation of the ratio of vertical and horizontal rainfall with wind speed, when the wind is perpendicular to the wall (SSE, S and SSW).

The experimental data obtained from these observations show that the ratio of the vertical and horizontal rainfall is proportional to the wind speed in heavy rain storms, and that the proportional constant is about 0.14, that is

$$R_w/R_h = 0.14\, u. \tag{6}$$

Fig. 3 shows the variation of this relation with wind direction. As is clear from this figure, the ratios are almost proportional to the wind speeds, but the proportional constant decreases with the increasing deviation of the wind direction away from the south or the line perpendicular to the wall.

The proportional constants for all wind directions are shown in vector form in Fig. 4. The ends of the vectors are approximately on a circle, as shown in this figure, which means that the cosine law can be applied to this constant. As the effective area of the collector on the wall to the wind is proportional to the cosine

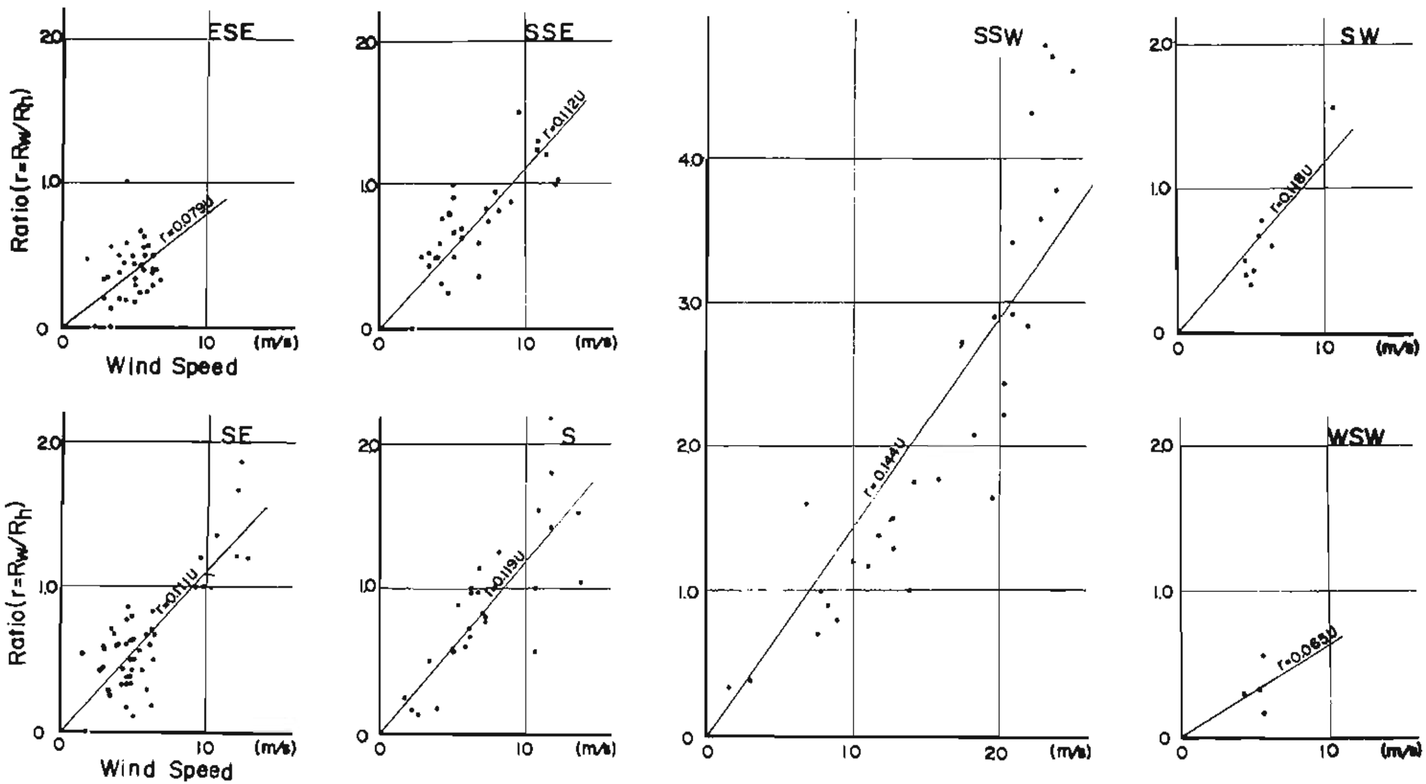

Fig. 3. Relations between the ratio of vertical and horizontal rainfall and wind speed for various wind directions.

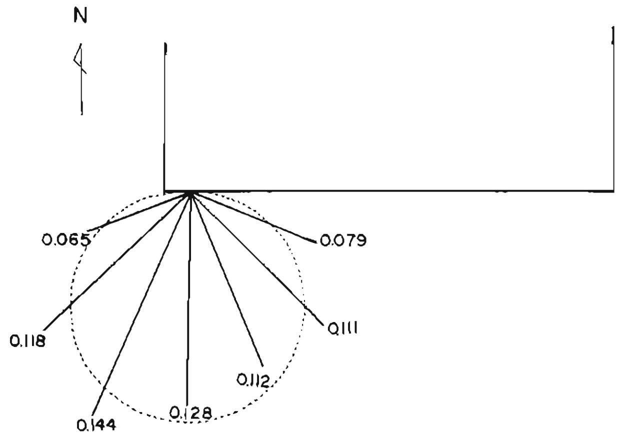

Fig. 4. The variation of the proportional constant with wind direction.

of the wind deviation away from the south, the relation shown as Eq. (6) holds good even when the wind is not perpendicular to the wall.

4. Discussion

The deposition of rain water on the surface of an obstacle in a wind is small if the size of the droplets is very small. But the efficiency of deposition may be expected to become large and to near unity in heavy rain in strong wind, by analogy to the results of studies on icing on aeroplanes.

According to field experiments with a real building, the deposition of rain water on a wall or the vertical rainfall is proportional to the product of the wind speed and the (horizontal) rainfall in heavy rain. The proportional constant is about 0.14.

From this relation, the efficiency of deposition of rain water on a wall is estimated to be near unity in heavy rain. However, more detailed studies are needed to clarify the relation of this efficiency to the shape and the scale of the building, to the radius of the raindrops, and to the wind speed.

For practical purposes, design criteria for water protection of windows can be deduced from the relation obtained in such studies if we know the design values of rainfall and wind speed in critical conditions.

Here, we must know whether extremely heavy rainfall is accompanied by strong wind or not. For this purpose the correlation coefficients between 6 min (horizontal) rainfall and wind speed were computed for all the runs and are shown in Table 1. The value is not definite and even differs in sign. This means that no difinite relation between wind strength and rainfall can be found in this case. But we can find the case which shows a good positive correlation between rainfall and wind speed in a typhoon[3], so we should expect that the extreme values of wind speed and of rainfall occur at the same time.

The extreme value of 10 min rainfall in Japan is 56 mm; this was observed at

Shionomisaki; and the maximum mean wind speed expected there is about 30 m/sec. Therefore, if we use the relation shown in Eq. (6), the maximum expected deposit of rain water on the wall will become about 23 liters m^{-2} min^{-1}. This value is much larger than the current Japanese design criteria for curtain walls, which is 4 liters m^{-2} min^{-1}. More climatological data are required to establish new design criteria.

References

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